

Manuscript: "Virtual Rain: A Unified Toolkit for High-Resolution Rainfall Simulation and Disaggregation"

Authors Reply

(in black Reviewers' comments; in blue Authors' comments; in red Authors' actions)

Reviewer 3

General Comments

This manuscript presents Virtual Rain, an integrated toolkit that combines a stochastic daily rainfall generator with a multiplicative random cascade for sub-daily disaggregation. The topic is relevant to stochastic hydrology. It fits well within the aims and scope of Geoscientific Model Development, particularly its interest in statistical geoscientific models, frameworks, and utility toolboxes. If carefully verified and documented, Virtual Rain could provide a valuable resource for researchers and practitioners who need long synthetic rainfall time series or high-resolution rainfall information.

The manuscript is clear and easy to follow. Its main novelty is implementing and integrating established methods rather than introducing a new stochastic rainfall formulation. This is a legitimate and potentially valuable contribution. It also means that software correctness, reproducibility, documentation, and cross-interface consistency are central to the paper. The current software package implementation would benefit from stronger evidence that the Python and R scripts (and the web platform) run in clean environments, are numerically consistent, and can reproduce the reported figures and tables.

The hydrological evaluation could also be strengthened in several focused ways. Calibration and diagnostic assessment currently rely on the same station record; the exponent n is obtained from the 15-min observations although the toolkit is presented as applicable in data-sparse settings; and a single 1000-year cascade realisation is compared with a 20-year observed record. These choices make it difficult to separate calibration from validation, disaggregation error from daily-generator error, and stochastic variability from record-length effects. Quantifying uncertainty in the GEV, derived IDF quantities, and cascade parameters would further improve the scientific interpretation and help the authors calibrate claims of robustness and transferability to the evidence available from one site.

I also reviewed the interactive discussion and appreciate the authors' constructive engagement with the two existing referee reports. The proposed additions – including clearer terminology, a dedicated Discussion, and more complete documentation – would improve the manuscript. I encourage the authors to incorporate those changes directly into the revised paper and software archive. In particular, formal implementation verification, a matched-length Module 2 ensemble, an observed-daily versus synthetic-daily comparison, quantitative uncertainty analysis, and optimizer/identifiability diagnostics would provide especially strong support for the software contribution. Where an additional analysis is not feasible, the corresponding claim should be narrowed, and the limitation stated transparently.

Overall, I found the concept behind Virtual Rain promising. I hope these comments are helpful in preparing a revised manuscript and software release that fully demonstrate the value of the toolkit. I therefore recommend major revision. This recommendation reflects the amount of verification and clarification still required, rather than a lack of potential value.

Authors' comment: We sincerely thank the Reviewer for the careful reading of the manuscript and for the positive evaluation of our work. We particularly appreciate the recognition of the potential value of Virtual

Rain as an integrated and accessible framework for stochastic daily rainfall simulation and sub-daily disaggregation. We agree that, given the methodological nature of the contribution, software verification, reproducibility, documentation, and consistency across the different implementations are essential aspects of the work. In the revised manuscript and accompanying software release, we have therefore carefully addressed these points and substantially improved the documentation and description of the implementation.

We also thank the Reviewer for the constructive comments concerning the hydrological evaluation and the distinction between calibration, validation, and stochastic uncertainty. Following these suggestions, we have revised the analyses and discussion to better clarify the role of the observed record, the information used for model calibration, and the interpretation of the comparison between observed and synthetic rainfall. Additional analyses and diagnostics have been included where feasible, while the corresponding limitations and assumptions have been more explicitly discussed where further validation could not be performed.

We also appreciate the Reviewer's consideration of the previous interactive discussion and the acknowledgement of our responses to the other referee reports. The revised manuscript incorporates the proposed improvements, including clearer terminology, an expanded Discussion section, additional methodological details, and improved software documentation. Particular attention has also been devoted to ensuring that the claims regarding robustness, transferability, and applicability in data-scarce conditions are appropriately supported by the analyses presented and, where necessary, more carefully qualified.

Overall, we believe that the Reviewer's comments, together with those received during the interactive discussion, have helped us substantially improve both the manuscript and the Virtual Rain software package. We sincerely thank the Reviewer for the detailed and constructive assessment and for the suggestions aimed at strengthening the scientific and practical contribution of the work.

Comment 1

Journal positioning, novelty, and version identification. Would the authors consider identifying the formal GMD manuscript type explicitly and aligning the framing with it? The submission appears best suited to a model-description paper or a development-and-technical paper. The title should also include the exact software/model version, as expected for model and software descriptions. In the Introduction, it would be helpful to distinguish clearly between (i) the methodological advances already established in the authors' earlier rainfall-generation and disaggregation papers; and, (ii) the new contribution of Virtual Rain, namely integration, interfaces, documentation, and implementation. A concise novelty table could make this distinction especially clear, accompanied by direct verification of the new implementation.

Authors' comment: We thank the Reviewer for this helpful comment. We would first like to clarify that the manuscript was already submitted under the GMD manuscript type "*Development and technical paper*", which we agree is the most appropriate category given the scope and objectives of Virtual Rain.

We also agree that the distinction between the previously established methodological developments and the specific contribution of the present manuscript should be made as explicit as possible. The previous version of the Introduction already stated that the objective of this work is not to develop or re-validate the underlying methodologies, but rather to provide their first integrated, reproducible, and user-friendly software implementation. Nevertheless, we agree that this distinction can be further strengthened.

In particular, CoSMoS-2s and the MRC disaggregation methodology should be clearly identified as previously developed methodological components, whereas the novelty of Virtual Rain lies in their software implementation and integration, the provision of Python and R computational workflows, the web-based interface, documentation, reproducible examples, and implementation verification.

We also agree with the Reviewer that the software version should be explicitly identifiable and that a concise table distinguishing previous methodological developments from the contributions of the present work can improve the positioning of the manuscript.

Authors' action: Following the Reviewer's suggestion, we have revised the title to explicitly identify the software version: "*Virtual Rain v1.0: A Unified Toolkit for High-Resolution Rainfall Simulation and Disaggregation*" (v1.0 will correspond to the version associated with the archived software release.)

We have also explicitly identified the manuscript type and further clarified the scope of the contribution in the Introduction. The corresponding paragraph now reads (lines 66-75):

Compared with the previous methodological studies, the novelty of the present contribution lies in the *in the development, implementation, integration, documentation, and verification of the Virtual Rain software framework, rather than in the development of new stochastic rainfall methodologies*. Virtual Rain provides the first integrated implementation of the complete CoSMoS-2s workflow (Module 1) and the complete MRC calibration and disaggregation workflow (Module 2) through standalone Python and R routines, complemented by an interactive web-based platform that reproduces the same computational workflow. *The specific developments introduced in the present work include the integration of the two previously independent methodological components, their implementation as accessible computational workflows, the development of user interfaces and supporting documentation, and the provision of reproducible examples and implementation-verification procedures. Table 1 summarizes the distinction between previously established methodological developments and the new software and technical contributions introduced by Virtual Rain v1.0.*

We have consequently added the following table to the Introduction:

Table 1. Methodological background and specific contributions of Virtual Rain v1.0.

<i>Component</i>	<i>Previous methodological development</i>	<i>Contribution of Virtual Rain v1.0</i>
<i>Daily rainfall simulation</i>	<i>CoSMoS framework and CoSMoS-2s formulation</i>	<i>Software implementation of the complete CoSMoS-2s workflow and its integration within Virtual Rain</i>
<i>Multifractal rainfall disaggregation</i>	<i>MRC methodology developed in previous studies</i>	<i>Implementation of the complete calibration and disaggregation workflow within the toolkit</i>
<i>Coupling of the two modules</i>	<i>Previously proposed methodological framework</i>	<i>First integrated software implementation allowing the modules to operate jointly or independently</i>
<i>Python/R workflows</i>	<i>Not previously available</i>	<i>Standalone, documented computational workflows with reproducible examples</i>
<i>Web interface</i>	<i>Not previously available</i>	<i>Interactive web-based implementation of the Virtual Rain workflow</i>

To further distinguish methodological novelty from software novelty, we have added the following clarification after the description of the two modules (lines 50-54):

While the methodological developments of CoSMoS-2s and the MRC model have already been presented and validated in the corresponding methodological studies, no integrated software implementation was previously available. *Therefore, neither CoSMoS-2s nor the MRC formulation is presented here as a new methodological contribution. Rather, Virtual Rain operationalizes these previously developed methodologies within a common computational framework, providing the interfaces, routines, documentation, and workflow required to apply them jointly or independently.*

Finally, we have strengthened the description of the role of the case study (lines 79-84):

The proposed software is demonstrated through a real-world case study involving a single rain gauge station. The purpose of the case study is to illustrate the implementation and application of the complete Virtual Rain workflow and to verify the consistency of the software outputs with the expected behavior of the underlying methodologies, rather than to provide a new methodological validation of CoSMoS-2s or the MRC model. *Consistent with the Development and technical paper scope, particular attention is therefore given to workflow reproducibility, implementation verification, and consistency among the computational interfaces.*

Comment 2

Software archive, licence, and executable documentation. I encourage the authors to issue a new frozen release that fully satisfies GMD's code and data requirements. The current Zenodo record provides a CC BY 4.0 record-level licence, but the source does not include an OSI-approved software licence (e.g., GPL 3). The archive would also be substantially more useful with a README, user manual, running examples, automated tests, dependency lock files, package versions, and documented software/hardware requirements. Please provide an explicit software licence, separate data licensing where appropriate, installation instructions, input schemas, expected outputs, complete end-to-end examples, environment files for Python and R, and a mapping between archived scripts and every manuscript figure/table. The Code and data availability section should cite the exact release bibliographically, state the licence, and identify the development/web location.

Authors' comment: We thank the Reviewer for this important comment. We agree that, particularly for a Development and technical paper, the software archive should provide not only permanent access to the source code and data, but also sufficient documentation to allow users to understand, execute, and reproduce the Virtual Rain workflow independently.

The routines and data used in the manuscript are permanently archived on Zenodo under DOI 10.5281/zenodo.22747568. We acknowledge the Reviewer's important distinction between the licence associated with the Zenodo record and an explicit software licence applying specifically to the source code. We also agree that the archive benefits from clearer executable documentation, information on software requirements and dependencies, explicit input/output descriptions, and instructions for reproducing the workflow.

We have therefore revised the Zenodo archive to improve its usability and reproducibility. In particular, we have added a dedicated README.txt file that provides a structured description of Virtual Rain, the contents of the archive, software requirements, input data, expected outputs, instructions for running Modules 1 and 2 independently and jointly, information on reproducibility and software verification, licensing information, data provenance, and citation instructions.

We also clarify the distinction between the licensing of the software and that of the rainfall data. The Virtual Rain source code was developed by the authors and is distributed under the GNU General Public License v3.0 or later (GPL-3.0-or-later). The rainfall data used for the case study originate from the Settore Idrologico e Geologico Regionale (SIR) – Regione Toscana and retain their original Creative Commons Attribution-ShareAlike 4.0 International (CC BY-SA 4.0) licence.

Authors' action: Following the Reviewer's suggestion, the Zenodo archive (DOI: 10.5281/zenodo.22747568) has been updated to improve the documentation and reproducibility of the software release.

In particular, we have added a README.txt file to the Zenodo archive. The README includes:

- an overview of Virtual Rain and its two-module architecture;
- a description of the files included in the archive;
- Python and R software requirements;
- descriptions of the required input data and expected outputs;
- step-by-step instructions for executing Module 1 and Module 2;

- instructions for running the complete Virtual Rain workflow;
- information for reproducing the case study presented in the manuscript;
- software verification guidance;
- explicit distinction between software and data licensing;
- data source and attribution information;
- citation information for the archived Virtual Rain release.

The software licensing information has also been clarified. The Virtual Rain source code is distributed under the GNU General Public License v3.0 or later (GPL-3.0-or-later), whereas the rainfall data used in the case study originate from the Settore Idrologico e Geologico Regionale (SIR) – Regione Toscana and are distributed under the Creative Commons Attribution-ShareAlike 4.0 International (CC BY-SA 4.0) licence.

The Code and data availability section of the manuscript has consequently been expanded and now reads:

The Virtual Rain source code, executable routines, documentation, and data used to reproduce the analyses presented in this manuscript are permanently archived on Zenodo (Cappelli et al., 2026; <https://doi.org/10.5281/zenodo.22747568>). The archived release corresponds to Virtual Rain v2 and includes the Python implementation of Module 1, the R implementation of Module 2, the case-study data, and a dedicated README.txt file providing software requirements, input and output descriptions, execution instructions, reproducibility guidance, licensing information, and citation instructions. The Virtual Rain source code is distributed under the GNU General Public License v3.0 or later (GPL-3.0-or-later). The rainfall data used in the case study originate from the Settore Idrologico e Geologico Regionale (SIR) – Regione Toscana and are distributed under the Creative Commons Attribution-ShareAlike 4.0 International (CC BY-SA 4.0) licence. To reproduce the analyses, users should download the archived release and follow the module-specific and complete-workflow instructions provided in README.txt. The archived software should be cited as: Cappelli, F., Grimaldi, S., Petroselli, A., and Santinami, E. (2026): Virtual Rain: A Unified Toolkit for High-Resolution Rainfall Simulation and Disaggregation, Version v2, Zenodo, <https://doi.org/10.5281/zenodo.22747568>.

We believe that these additions substantially improve the transparency, accessibility, and reproducibility of the archived Virtual Rain release and directly address the Reviewer's concerns regarding executable documentation and licensing.

Comment 3

Formal software verification and cross-interface equivalence. A particularly valuable addition would be a formal demonstration that the standalone routines and the webplatform implement the same algorithms. Could the authors add archived golden test cases with common inputs, parameters, seeds, expected outputs, numerical tolerances, and checksums? The tests could compare the Python/R routines with the web interface. Such numerical tests would complement the current screenshots and provide readers with much stronger evidence of cross-interface equivalence.

Authors' comment: We thank the Reviewer for this valuable suggestion. Regarding software verification, the focus of this work is indeed on verifying the correctness and consistency of the software implementation. The standalone Python and R routines and the web platform implement the same computational workflow, methodological formulations, and parameterization, thereby ensuring methodological consistency across the different software components.

Both modules of Virtual Rain involve stochastic simulation. Module 1 generates stochastic daily rainfall realizations, while Module 2 uses a stochastic multiplicative cascade to generate sub-daily rainfall. Consequently, comparisons across interfaces require particular attention to the random-number generation process and, in particular, to the initialization of the random seed. Without controlling this component, different individual realizations may be obtained even when identical inputs and model parameters are specified; such differences do not necessarily indicate inconsistencies in the implemented algorithms.

To further verify cross-interface consistency, we performed a controlled comparison for Module 2 using identical input data, model parameters, and random seed in the standalone R routine and in the Virtual Rain web platform. Under these controlled conditions, the resulting outputs coincide, providing direct numerical evidence that the two interfaces implement the same MRC computational procedure. This comparison also confirms that differences between stochastic realizations obtained without explicitly controlling the seed can arise from random-number initialization rather than from differences in the underlying methodological implementation.

More generally, we consider it important to distinguish between numerical reproducibility under controlled random-number initialization and statistical consistency across independent stochastic realizations. When the random-number sequence is controlled, direct numerical comparison provides a stringent implementation check, as demonstrated for Module 2. When independent stochastic realizations are generated, point-by-point equality is not expected, and cross-interface consistency is more appropriately assessed through the reproduction of the statistical properties prescribed by the underlying models, including rainfall intermittency, marginal distributions, temporal dependence, preservation of daily rainfall totals during disaggregation, and the targeted sub-daily rainfall variability.

Authors' action: Following the Reviewer's comment, we have clarified this distinction in the revised manuscript and software documentation. In particular, we now explicitly state that cross-interface verification is based on consistency of the computational workflow, parameterization, deterministic intermediate quantities where applicable, and statistical properties of the resulting stochastic simulations, rather than on exact equality of individual simulated realizations.

The following clarification has been added to the manuscript in Section 3.3 (lines 390-406):

Importantly, the standalone Python and R routines and the Virtual Rain web platform implement the same methodological formulations, computational workflow, and model parameterization. Because both daily rainfall generation and sub-daily disaggregation involve stochastic simulation, individual synthetic realizations are not expected to be numerically identical across the different software environments, even when the same input data and model parameters are used. Cross-interface consistency should therefore be interpreted in terms of equivalence of the implemented algorithms and parameterization and, for stochastic outputs, reproduction of the same target statistical properties rather than point-by-point equality of the generated series. These properties include rainfall intermittency, marginal distributions, temporal dependence, preservation of daily rainfall totals during disaggregation, and the statistical characteristics of sub-daily rainfall prescribed by the MRC model. For deterministic components of the workflow, consistency can instead be assessed through direct comparison of the corresponding parameters and intermediate computational outputs.

By combining computational routines with an intuitive graphical interface, Virtual Rain reduces the technical barrier associated with coding while preserving the flexibility of the proposed modelling framework. *The web platform therefore provides an alternative interface to the same computational framework rather than a separate modelling implementation.* It supports practical model application while facilitating the interpretation of the underlying stochastic processes, parameter choices, and diagnostic outputs. Overall, Virtual Rain bridges methodological flexibility and practical usability, making the framework accessible for research, professional, and educational purposes.

We have also clarified this aspect in the software documentation so that users do not interpret differences between individual stochastic realizations as inconsistencies between the implementations.

Where deterministic quantities are produced by the workflow, such as estimated/calibrated model parameters, input transformations, and quantities that do not depend on random sampling, these provide a more appropriate basis for direct numerical comparison across interfaces. For stochastic outputs, verification instead focuses on whether simulations generated under equivalent configurations reproduce the same prescribed statistical behaviour.

We believe this distinction provides a more appropriate verification framework for Virtual Rain: numerical equivalence for deterministic components and statistical equivalence for stochastic outputs.

Comment 4

Calibration, verification, and validation terminology. Could the authors clarify the evaluation design and associated terminology? The same 2001-2020 record is used to choose the seasonal structure, fit marginal and dependence models, estimate key quantities, and assess performance. Agreement at fitted lags or for fitted summary properties is therefore best described as a calibration diagnostic rather than independent validation. A blocked or split-sample assessment would strengthen the paper. Alternatively, the case study could be described consistently as a calibration and software-demonstration exercise.

Authors' comment: We thank the Reviewer for this important clarification. We agree that the terminology used in the manuscript should more clearly distinguish between calibration diagnostics, software verification, and independent model validation.

As correctly noted by the Reviewer, the same 2001–2020 observational record is used to define the seasonal structure, estimate the marginal and dependence properties, calibrate the model parameters, and subsequently compare the observed and simulated statistical characteristics. Therefore, the comparison presented in the case study should not be interpreted as an independent validation or as an assessment of predictive performance on unseen data.

The subsequent comparison between observed and simulated statistics is instead intended to verify the ability of the calibrated stochastic model to reproduce the target statistical characteristics, as well as to demonstrate the correct implementation of the Virtual Rain workflow. This interpretation is also consistent with the main objective of the present Development and technical paper, which focuses on the implementation and operation of the software rather than on providing a new independent validation of the underlying stochastic methodologies.

We therefore agree with the Reviewer that describing the case study consistently as a calibration and software-demonstration/verification exercise is more appropriate and avoids possible ambiguity.

Authors' action: Following the Reviewer's suggestion, we have revised the manuscript throughout to ensure consistent use of the terms calibration, diagnostic assessment, software verification, and validation. In particular, references that could imply an independent validation based on the 2001–2020 record have been removed or reformulated.

We have added the following clarification to the description of the case study in Section 4 (lines 416-420):

The 2001–2020 observational record is used both for model calibration and for the subsequent diagnostic comparison with the simulated series. The comparison between observed and simulated statistics is intended to verify the ability of the calibrated stochastic model to reproduce the target statistical characteristics and to demonstrate the correct implementation of the Virtual Rain workflow, rather than to assess predictive performance on an independent validation dataset.

We have also revised the corresponding terminology in the Results and Discussion sections so that agreement between observed and simulated quantities estimated from the same calibration record is consistently referred to as calibration performance, diagnostic agreement, or software/model reproduction assessment, rather than independent validation.

These changes are intended to avoid any confusion regarding the evaluation design and to ensure that the terminology accurately reflects the evidence provided by the case study.

Comment 5

Provenance of n and the claimed data-sparse pathway. Could the authors state unambiguously how the scaling exponent $n = 0.251$ was obtained and adjust the related claims accordingly? The author response confirms that n was estimated from the observed 15-min series. Thus, the present case study illustrates the data-rich pathway but does not yet demonstrate calibration without sub-daily observations. As a consequence, Table 3 should not

imply that the sub-daily record was used only for evaluation. If feasible, a genuinely data-sparse experiment in which n and $a(T)$ are obtained from independent (e.g., regional) information would be highly informative. Otherwise, the manuscript can distinguish clearly between a demonstrated case-study pathway and a software capability available to future users.

Authors' comment: We thank the Reviewer for highlighting this important point. We agree that the manuscript should distinguish more clearly between the data-rich pathway demonstrated in the present case study and the broader data-sparse capability of the software.

As correctly noted by the Reviewer, in the present case study the scaling exponent $n = 0.251$ was not derived independently from regional information, but was estimated directly from the available sub-daily observations. Therefore, the case study demonstrates the use of Virtual Rain under conditions where sub-daily information is available for estimating the IDF scaling exponent, and it should not be interpreted as a direct demonstration of the fully data-sparse pathway.

The value of n was obtained from the observed sub-daily rainfall record by first constructing depth-duration-frequency information from the available high-resolution data. Specifically, rainfall was aggregated at durations of 1, 3, 6, 12, and 24 h, annual maxima were extracted for each duration, and the corresponding depth-duration relationships were linearized in logarithmic coordinates. The scaling exponent was then estimated using a least-squares procedure with the additional constraint of parallelism among the linearized curves, following the approach illustrated in the methodological scheme reported in the referenced papers material. In this formulation, the slope of the linearized DDF/IDF relationships provides the imposed exponent n .

Accordingly, in the present workflow n must be interpreted as an external calibration input to Module 2, not as an output estimated internally by the MRC model. Virtual Rain nevertheless allows this input to be supplied either from local sub-daily observations, as done here, or from external regional IDF/DDF information when local high-resolution observations are unavailable.

Authors' action: Following the Reviewer's suggestion, we have revised the manuscript to make the provenance and role of n unambiguous.

In Section 3.2 (lines 293-296), the description of `GEV_Fitting()` has been revised as follows:

★ **M2.1:** `GEV_Fitting(data, starting_day = '2000-01-01', num_of_days_for_truncation = 183, n_par = 0.3)`

Goal: Estimate the extreme rainfall statistics and scaling parameters required for MRC calibration.

Inputs:

- **data:** observed rainfall time series;
- **starting_day:** starting date of the time series used to construct the temporal index;
- **num_of_days_for_truncation:** threshold used to exclude incomplete initial or final years;
- **n_par:** *externally imposed scaling exponent representing the slope of the IDF/DDF relationships. This parameter can be estimated from local sub-daily observations or obtained from independent regional IDF/DDF information. In the present case study, n was estimated from the observed sub-daily record and therefore represents a calibration input rather than a model output.*

The case-study description has also been revised to clarify how $n = 0.251$ was obtained (lines 539-547):

Besides the daily rainfall series, Module 2 requires the scaling exponent n , representing the slope of the IDF/DDF relationship. This parameter is an imposed input of the `GEV_Fitting()` routine and can either be estimated from available sub-daily rainfall observations or obtained from external sources,

such as regional IDF/DDF relationships. In the present case study, $n = 0.251$ was estimated from the observed sub-daily rainfall record. Specifically, precipitation was aggregated at durations of 1, 3, 6, 12, and 24 h, annual maximum rainfall depths were extracted for each duration, and the resulting DDF relationships were linearized in logarithmic coordinates. The common slope was then estimated by least squares while imposing parallelism among the linearized curves. The resulting value $n = 0.251$ was used, together with the synthetic daily rainfall series generated by Module 1, to calibrate the MRC disaggregation model. Consequently, n should be regarded as an imposed calibration input rather than as a model output.

We have revised the description of the Module 2 case study to clarify the dual role of the observed 15-minute rainfall record. Specifically, the high-resolution observations are used (i) to estimate the scaling exponent n , which is subsequently imposed as an input to the MRC calibration procedure, and (ii) as a benchmark for the diagnostic assessment of the disaggregated rainfall series. The manuscript therefore no longer describes the sub-daily observations as being used exclusively for evaluation.

We have also revised the statements concerning the applicability of Virtual Rain in data-sparse conditions. The manuscript now explicitly distinguishes between (i) the data-rich pathway demonstrated in the present case study, in which n is estimated from local sub-daily observations, and (ii) the data-sparse pathway supported by the software, in which n can instead be supplied from independent external information, such as regional IDF/DDF relationships. The latter represents a capability of the software but is not explicitly evaluated in the present case study. Accordingly, statements that could have suggested that the current application itself demonstrates a fully data-sparse calibration have been revised.

The corresponding paragraph now reads (lines 582-592):

Finally, a comprehensive summary of the disaggregation results is provided in Table 4. *The observed 15-minute rainfall series serves two distinct purposes in the present case study: (i) it is used to estimate the target scaling exponent n , which is subsequently imposed as an input to the MRC calibration procedure, and (ii) it provides the benchmark for the diagnostic comparison with the disaggregated rainfall series.* ~~The observed 15-minute rainfall series is used as a benchmark for comparison and to estimate the target scaling exponent ($n = 0.251$), whereas the calibration of the~~ The MRC parameters (C_β , C_{LN} , and D) is performed independently through the MRC calibration procedure using the synthetic daily rainfall series generated by Module 1 *together with the imposed value of n . Therefore, the present application represents the data-rich pathway available in Virtual Rain, in which local sub-daily observations are available to estimate n . When such observations are unavailable, the software also allows n to be supplied from independent external information, such as regional IDF/DDF relationships; however, this data-sparse pathway is a software capability and is not explicitly evaluated in the present case study. The subsequent comparison between the observed and disaggregated rainfall series is intended as a diagnostic assessment of the implemented workflow rather than as an independent validation of the MRC methodology.*

Comment 6

Module 2 evaluation, record-length comparability, and error propagation. Could the authors make the Module 2 comparison more directly comparable in record length? A single 1000-year cascade realisation is currently compared with a 20-year observed 15-min record, so differences in maxima and upper percentiles may reflect both record length and stochastic variability. A matched-length ensemble, for example, many 20-year realisations, would allow the authors to report observed ranks, bias, interval coverage, and Monte Carlo uncertainty.

Authors' comment: We thank the Reviewer for this valuable suggestion. We agree that a matched-length ensemble, for example based on multiple 20-year realizations, would provide a more direct comparison with the observed 20-year record and would allow the effects of stochastic variability and record length on upper percentiles and rainfall maxima to be quantified more explicitly.

We did not include this additional analysis in the present manuscript because an extensive ensemble-based diagnostic assessment of the statistical properties of the disaggregated series has already been presented in

Cappelli et al. (2025a), Appendix, Case Study 3. Such an ensemble analysis is also computationally demanding, particularly when long high-resolution rainfall series and multiple realizations are generated. Since the primary objective of the present Development and technical paper is to provide an integrated and computationally efficient implementation of the Virtual Rain workflow, rather than to repeat the methodological validation of the MRC model, we preferred not to incorporate this computationally intensive diagnostic into the standard Virtual Rain routines or repeat the full analysis in the present study.

Nevertheless, we agree that the different lengths of the observed and simulated records must be clearly acknowledged when interpreting Table 3. The comparison between a single 1000-year synthetic realization and the 20-year observed record should not be used to infer direct agreement in sample-dependent quantities such as absolute maxima or very high empirical percentiles. We have therefore revised the manuscript to explicitly state this limitation and to direct readers interested in a more comprehensive assessment of the stochastic variability of the disaggregation procedure to the corresponding analysis in Cappelli et al. (2025a).

Authors' action: Following the Reviewer's comment, we have revised the discussion surrounding Table 4 (formerly Table 3) to make the purpose and limitations of the comparison more explicit. In particular, we now clarify that the 1000-year versus 20-year comparison is primarily intended as a *software and calibration diagnostic*, and that differences in sample-dependent extreme statistics cannot be interpreted independently of record-length and stochastic-sampling effects.

The corresponding text has been revised as follows (lines 598-605):

Table 4 compares the observed 20-year rainfall series at 15-minute resolution with a single 1000-year synthetic realization. Consequently, sample-dependent quantities, particularly absolute maxima and very high empirical percentiles, are not directly comparable between the two records because their sampling variability depends strongly on record length. A matched-length ensemble would provide a more appropriate framework for quantifying the distribution of these diagnostics and the associated Monte Carlo uncertainty. Such an ensemble-based assessment is not included in the present software-oriented study because it requires a substantially larger computational effort and would duplicate the extensive diagnostic analysis of the MRC methodology already presented in Cappelli et al. (2025a, Appendix, Case Study 3), to which interested readers are referred.

As expected, larger differences emerge when considering extreme rainfall properties. *These differences should not be attributed exclusively to model performance, because they may arise from both the different record lengths and stochastic variability.* In the integrated Virtual Rain workflow, they may additionally reflect uncertainty propagated from the synthetic daily rainfall series generated by Module 1, which constitutes the input to the MRC calibration procedure. Therefore, the current case study does not allow the effects of record length, stochastic cascade variability, and uncertainty inherited from daily rainfall generation to be fully disentangled. The disaggregated time series exhibits higher maximum rainfall accumulations across the considered aggregation durations, and the empirically estimated α -coefficients are generally larger than those derived from the observed record.

Nevertheless, the principal calibration targets are reproduced consistently. Both the dry frequency (p_0) and the scaling exponent (n) are preserved by the implemented workflow, supporting the ability of the two modules to reproduce rainfall intermittency and the prescribed scaling properties while remaining consistent with the target IDF relationships. *A more extensive assessment based on multiple stochastic realizations and matched record lengths, including the variability of the resulting rainfall statistics, is available in Cappelli et al. (2025a, Appendix, Case Study 3) and is not repeated here.* The application of the MRC model directly to observed daily rainfall series, thereby isolating the performance of the disaggregation methodology from the uncertainty introduced by Module 1, is presented and discussed in Cappelli et al. (2026b).

Overall, within the context of this software paper, the results are intended to demonstrate the correct implementation and operation of the integrated Module 1–Module 2 workflow rather than to provide a new methodological validation of the MRC model. *Accordingly, Table 3 should be interpreted as a diagnostic illustration of the implemented workflow, while the more computationally intensive ensemble-based evaluation of stochastic uncertainty and record-length effects is documented in the previous methodological study.*

The caption of Table 4 has been updated accordingly, as the previous version could still suggest direct comparability between the two records.

Table 4. Diagnostic comparison of summary statistics, ACS coefficients, accumulated maxima, and IDF parameters for the observed 20-year rainfall series at 15-minute resolution and a 1000-year synthetic rainfall realization generated by the MRC disaggregation model. Owing to the different record lengths, sample-dependent extreme statistics should not be interpreted as directly comparable estimates.

Comment 7

Complete mathematical description of the cascade and calibration objective. Could the authors expand the mathematical description so that an independent reader can reproduce Module 2? The current manuscript does not fully define the beta-lognormal weight distribution, cascade recursion, conservation rule, theoretical IDF expression, calibration objective, duration and return-period weights, etc. References to the earlier papers are useful, but the implementation-specific choices that determine numerical output should also be stated in this manuscript. Please present the full equations and define every symbol, unit, constraint, objective-function component, convergence criterion, and preprocessing step.

Authors' comment: We thank the Reviewer for this thoughtful comment and understand the importance of providing sufficient methodological information to make the computational workflow transparent and reproducible.

As clarified in our response to Comment 1, the manuscript was submitted under the GMD manuscript type “**Development and technical paper**”, which we consider the most appropriate category given the scope and objectives of Virtual Rain. The primary objective of the present contribution is to describe, document, and make accessible the software implementation and integration of previously developed methodologies, rather than to introduce or re-derive the underlying stochastic formulations.

In particular, the mathematical formulation of the MRC model implemented in Module 2—including the beta-lognormal cascade formulation, cascade recursion and conservation properties, theoretical IDF relationships, and calibration strategy—has already been presented in detail in Cappelli et al. (2025a) and further discussed and applied in Cappelli et al. (2025b). Reproducing the complete mathematical derivation in the present manuscript would therefore substantially duplicate material already available in the methodological papers and would increase the length and technical complexity of a manuscript whose primary focus is the development and documentation of the Virtual Rain software framework.

Nevertheless, we agree with the Reviewer that readers should be able to identify unambiguously the mathematical formulation implemented by Virtual Rain and trace each computational component to its methodological source. We have therefore strengthened Section 2.2 (Module 2 – Sub-Daily Rainfall Disaggregation Model) by explicitly identifying the formulation implemented in the software and providing more direct references to the corresponding methodological equations and calibration procedure in Cappelli et al. (2025a,b). Implementation-specific information required to execute the model is instead documented in the subsequent software-description section and in the archived software documentation.

Authors' action: Following the Reviewer's suggestion, we have revised Section 2.2 – Module 2: Sub-Daily Rainfall Disaggregation Model to clarify the relationship between the mathematical formulation described in the previous methodological studies and its implementation in Virtual Rain.

In particular, the section now explicitly identifies Cappelli et al. (2025a) as the primary reference for the complete mathematical definition of the beta-lognormal cascade weights, cascade recursion, rainfall-conservation rule, theoretical IDF formulation, and calibration objective, with additional reference to Cappelli et al. (2025b) where appropriate.

The following clarification has been added to Section 2.2:

This module is designed to disaggregate a simulated (by Module 1) or observed daily rainfall time series into high-resolution sub-daily time series using a multifractal random cascade (MRC) model (Cappelli et al., 2025a,b) (Figure 3). The approach assumes that rainfall intensity evolves as a multiplicative cascade process, in which the mean intensity at each temporal scale is redistributed through random weights with prescribed statistical properties. These weights follow a beta-lognormal distribution. The MRC model is characterized by three parameters: C_β , controlling intermittency and the proportion of dry intervals; C_{LN} , governing lognormal variability and intensity fluctuations; and D , representing the outer-scale parameter that defines the range of multifractal behavior.

The complete mathematical formulation of the MRC model adopted in Virtual Rain, including the beta-lognormal weight distribution, recursive cascade construction, conservation rule, theoretical multifractal IDF formulation, and calibration objective, is provided in Cappelli et al. (2025a,b). The present section summarizes the elements required to understand the role of Module 2 within Virtual Rain, while avoiding duplication of the complete methodological derivation already reported therein. Virtual Rain implements this formulation without introducing modifications to the underlying MRC model; implementation-specific choices and the corresponding input parameters are documented in the software-description section and in the archived software documentation.

Rather than calibrating these parameters using high-resolution rainfall observations, the implemented workflow derives them from IDF relationships, following Cappelli et al. (2025a). IDF curves are typically expressed as $i(d,T) = a(T)d^{n-1}$, where $i(d,T)$ is the rainfall intensity associated with duration d and return period T , n is the scaling exponent, and $a(T)$ is the return-period-dependent coefficient. *The theoretical relationship linking the MRC parameters to the IDF scaling properties, together with the objective function used for their calibration, parameter constraints, and optimization procedure, follows the formulation given in Cappelli et al. (2025a,b).* By matching theoretical multifractal IDF relationships to empirical IDF curves, it is possible to estimate the MRC parameters without requiring a continuous sub-daily rainfall record for their calibration.

The cascade procedure is applied independently to each simulated day, ensuring exact preservation of daily rainfall totals while generating physically consistent sub-daily variability. *The cascade recursion and conservation condition are those defined in Cappelli et al. (2025a,b), to which readers are referred for the complete mathematical derivation and definition of all associated variables.*

For reproducibility, the specific input variables, parameter units and constraints, preprocessing operations, optimization settings, convergence criteria, and output structure used by the Virtual Rain implementation are reported in Section 3 and in the README accompanying the archived software release.

Comment 8

Outer-scale parameter and daily cascade consistency. Could the authors explain how the fitted outer-scale parameter $D = 286.2$ h (approximately 12 days) should be interpreted when the multiplicative cascade is applied independently within each day? Because the fitted outer scale is substantially longer than the modelling block, readers may reasonably question how multi-day structure is represented in the sub-daily generation process. Please clarify the theoretical role of D in the implemented daily cascade, demonstrate consistency with the published formulation, and, if possible, provide a sensitivity or diagnostic test. If the implementation is valid only for a restricted range of D or cascade blocks, those constraints should be stated and enforced in the code.

Authors' comment: We thank the Reviewer for this important observation. We agree that the interpretation of the fitted outer-scale parameter $D = 286.2$ h should be clarified, particularly because the cascade is subsequently applied independently to individual daily rainfall amounts.

In the implemented MRC formulation, D is an outer-scale parameter involved in the IDF-based calibration of the multifractal model and should not be interpreted as the duration of the temporal block explicitly disaggregated by the cascade. The three parameters C_β , C_{LN} , and D are jointly estimated through a numerical

optimization procedure that minimizes the discrepancy between the theoretical multifractal IDF relationships and the target IDF information.

During this calibration, D enters the theoretical formulation through the scale ratio D/d , where d represents the rainfall duration considered in the IDF relationship. Therefore, the fitted value $D = 286.2\text{h}$ identifies the outer scale associated with the calibrated multifractal scaling regime; it does not imply that the algorithm generates or disaggregates a continuous 286.2 h rainfall block.

Once the calibration has been completed, the actual stochastic disaggregation of the daily rainfall amounts is governed by the calibrated C_β and C_{LN} parameters. Each daily rainfall amount is independently disaggregated within its 24h interval while preserving the corresponding daily total. Consequently, $D > 24\text{h}$ is not inconsistent with the daily cascade implementation and does not imply that multi-day rainfall structure is explicitly generated by Module 2. The complete theoretical role of D and its relationship with the MRC calibration equations are described in Cappelli et al. (2025a,b), whose formulation is implemented in Virtual Rain.

Given the Development and technical scope of the present manuscript, we prefer not to reproduce the complete mathematical derivation already provided in the methodological paper. However, we agree that the distinction between the calibration role of D and the daily disaggregation block should be made explicit.

Authors' action: Following the Reviewer's suggestion, we have added a concise clarification to Section 2.2 – Module 2: Sub-Daily Rainfall Disaggregation Model (lines 128-152):

These weights follow a beta-lognormal distribution. The MRC model is characterized by three parameters: C_β , controlling intermittency and the proportion of dry intervals; C_{LN} , governing lognormal variability and intensity fluctuations; and D , representing the outer-scale parameter that defines the range of multifractal behavior. **Importantly, D represents a scaling parameter of the theoretical multifractal formulation and should not be interpreted as the duration of the rainfall block subsequently disaggregated by the cascade.** Rather than calibrating these parameters using high-resolution rainfall observations, the implemented workflow derives them from IDF relationships, following Cappelli et al. (2025a). IDF curves are typically expressed as $i(d, T) = a(T)d^{n-1}$ where $i(d, T)$ is the rainfall intensity associated with duration d with return period T , and n is a scaling exponent constant with $0 < n < 1$, and $a(T)$ is a function independent of d . **The parameters C_β , C_{LN} , and D are jointly estimated through numerical optimization by matching the theoretical multifractal IDF relationships to the target IDF information. Within this calibration, D enters the theoretical formulation through the scale ratio D/d (Cappelli et al., 2025a,b).** By matching theoretical multifractal IDF relationships to empirical IDF curves, it is possible to estimate C_β , C_{LN} , and D without relying on sub-daily calibration data.

The cascade procedure is applied independently to each simulated day, ensuring exact preservation of daily rainfall totals while generating physically consistent sub-daily variability. **Once the MRC parameters have been calibrated, the stochastic redistribution within each daily block is governed by C_β and C_{LN} ; therefore, a fitted value of D greater than 24 h does not imply that a multi-day cascade of duration D is explicitly simulated.**

Comment 9

Discussion, limitations, and strength of claims. I support the authors' proposal in the interactive discussion to add a dedicated Discussion. This section could distinguish clearly between validation of the underlying methods and verification of the present implementation, while addressing single-site evidence, seasonal-boundary effects, error propagation between modules, the outer-scale issue, parameter uncertainty and identifiability, data-sparse versus data-rich use, failure modes, supported temporal resolutions, and comparison with the prior 70-station framework paper. Claims of general robustness, transferability across hydroclimates, reliability, and adaptation should be calibrated to the present evidence or explicitly attributed to earlier methodological studies. A balanced Discussion of this kind would considerably strengthen the manuscript.

Authors' comment: We thank the Reviewer for this constructive comment and for supporting the inclusion of a dedicated Discussion section. We agree that such a section provides an appropriate place to

distinguish more clearly between the methodological validation reported in the previous studies and the implementation verification performed in the present Development and technical paper.

Following this suggestion, we have expanded the Discussion to provide a more balanced interpretation of the evidence presented in the manuscript. In particular, we now explicitly discuss the single-site nature of the case study, the implications of seasonal stratification, uncertainty propagation between Modules 1 and 2, the interpretation of the MRC outer-scale parameter D , parameter uncertainty and identifiability, the distinction between data-rich and data-sparse applications, and the limitations associated with the comparison of observed and synthetic records of different lengths.

We have also revised statements concerning robustness, transferability, reliability, and applicability.

Where these properties have been demonstrated in previous methodological studies, they are now explicitly attributed to those studies rather than inferred from the present single-site software demonstration. Accordingly, the results presented here are interpreted primarily as evidence of the correct implementation and operation of the integrated Virtual Rain workflow.

Authors' action: Following the Reviewer's suggestion, we have substantially expanded *Section 5 – Discussion*. The revised section now reads:

5 Discussion

The primary objective of Virtual Rain is not to introduce new stochastic rainfall methodologies, but to provide an operational and reproducible implementation of previously developed approaches within a unified software environment. *Accordingly, the case study presented here should be interpreted primarily as a calibration, diagnostic, and software-verification exercise rather than as an independent validation of the underlying CoSMoS-2s and MRC methodologies. The same observational information used for model configuration and calibration is also used for the subsequent diagnostic assessment. The comparison between observed and simulated statistics is therefore intended to verify whether the implemented workflow reproduces the statistical characteristics prescribed during calibration, rather than to assess predictive performance on an independent validation dataset. Broader methodological evaluations of the underlying rainfall-generation and disaggregation approaches are reported in the corresponding previous studies.*

An important outcome of this work is that several methodological choices, which may remain implicit when stochastic models are applied within research-specific implementations, become explicit user decisions within Virtual Rain. Consequently, the software translates the flexibility of the underlying methodologies into a structured operational workflow. The user must specify or evaluate several key configuration elements, including (i) the seasonal partition, (ii) the marginal distribution of non-zero rainfall, (iii) the representation of the autocorrelation structure, (iv) the AR model order, (v) the imposed scaling exponent n , (vi) the return periods adopted during MRC calibration, and (vii) the length and temporal resolution of the rainfall series. These choices involve trade-offs among statistical representation, parameter-estimation uncertainty, computational efficiency, and data availability.

The seasonal partition represents one of the most influential configuration choices. Increasing the number of seasonal groups may improve the representation of the annual rainfall cycle, but simultaneously reduces the amount of data available for estimating marginal distributions and dependence properties within each season. Conversely, grouping consecutive months increases the sample available for parameter estimation at the expense of a less detailed representation of intra-annual variability. *Transitions between independently calibrated seasons may also introduce discontinuities in model parameters or dependence properties at seasonal boundaries. Virtual Rain therefore provides diagnostic information to support the user in selecting a seasonal structure appropriate to the available record and application rather than assuming that a single partition is universally optimal.*

A similar compromise characterizes the selection of the wet-state marginal distribution. Candidate distributions are evaluated within the seasonal calibration procedure, while a common distributional family can be adopted across seasons to improve consistency and interpretability and to limit unnecessary model complexity. *The selected distribution and its fitted parameters remain subject to sampling uncertainty, particularly when seasonal stratification leaves relatively few wet observations. Consequently, differences among*

similarly performing candidate distributions should not necessarily be interpreted as evidence of a uniquely identifiable marginal model.

The representation of temporal dependence also reflects a balance between flexibility and operational simplicity. In the present application, the empirical ACS structure was adopted because it provided close agreement with the dependence properties of the calibration record without requiring an additional parametric correlation model. Virtual Rain nevertheless allows a parametric ACS to be adopted when a smoother analytical representation is preferred. Similarly, the autoregressive order should be interpreted as a model-configuration parameter rather than as a uniquely identifiable physical characteristic of the rainfall process. Diagnostic comparisons at lags beyond those explicitly included in the autoregressive formulation can provide additional information on how effectively temporal persistence is propagated by the calibrated stochastic generator.

The MRC disaggregation module follows the same general philosophy. The scaling exponent n is treated as an imposed calibration input and may, in principle, be estimated from local sub-daily observations or obtained from external information such as regional IDF/DDF relationships. In the present case study, however, $n = 0.251$ was estimated from the available 15-min observations. The application presented here therefore represents the data-rich pathway and should not be interpreted as an empirical demonstration of calibration in the complete absence of local sub-daily observations. The possibility of supplying independently derived regional scaling information represents a capability of the software that remains to be evaluated explicitly in data-sparse applications.

The interpretation of the MRC outer-scale parameter D also deserves clarification. The parameter D is jointly estimated with C_β and C_{LN} during the numerical optimization of the theoretical multifractal IDF relationships and enters the calibration through the scale ratio D/d , where d denotes rainfall duration. It therefore represents the outer scale of the calibrated multifractal scaling regime rather than the duration of the rainfall block explicitly disaggregated by the cascade. In the present case study, the fitted value $D = 286.2\text{h}$ consequently does not imply that a continuous 286.2h cascade is simulated. Following calibration, individual daily rainfall amounts are independently disaggregated using the calibrated cascade parameters while preserving their daily totals. The theoretical interpretation and sensitivity of D are discussed more extensively in the original methodological formulation (Cappelli et al., 2025a).

The integrated use of Modules 1 and 2 introduces an additional source of uncertainty that is important when interpreting the final high-resolution rainfall series. Module 2 receives the synthetic daily rainfall generated by Module 1; consequently, departures generated during daily rainfall simulation may propagate into the subsequent disaggregation stage. Virtual Rain also allows Module 2 to be applied directly to observed daily rainfall, thereby avoiding this specific source of propagated uncertainty when reliable daily observations are available. The present integrated case study does not formally partition the total error into contributions from daily rainfall generation, MRC calibration, and stochastic cascade variability. Application of the MRC model directly to observed daily rainfall, which allows the disaggregation component to be examined separately, is presented in the corresponding methodological study.

Parameter uncertainty represents another limitation of the current implementation. Marginal, dependence, extreme-value, and cascade parameters are represented through point estimates in the operational workflow, and uncertainty in these estimates is not currently propagated through the complete Module 1–Module 2 chain. Moreover, combinations of MRC parameters may provide similarly performing solutions to the numerical calibration problem, making parameter identifiability an aspect that should be considered when interpreting individual fitted values. The current implementation should therefore be regarded as providing an operational calibrated solution rather than a complete probabilistic characterization of parameter uncertainty.

The temporal resolution attainable through Module 2 is determined by the cascade structure and by the configuration supported by the implementation. Accordingly, Virtual Rain should be applied only at temporal resolutions compatible with the implemented cascade hierarchy and the assumptions of the underlying MRC formulation. Extrapolation to resolutions or

cascade configurations not explicitly supported by the software should not be assumed to be valid without additional evaluation. The software documentation identifies the supported inputs and configuration options and should be consulted when applying the toolkit outside the example configuration considered here.

The present case study is deliberately limited to a single rain-gauge station and therefore cannot, by itself, establish general transferability across different hydroclimatic regimes. Claims regarding the broader performance of the underlying stochastic methodologies should consequently be interpreted in the context of the multi-site and methodological evaluations reported in the previous studies, rather than as conclusions derived from the present single-site demonstration. In particular, the previous large-sample framework applications provide complementary evidence on performance across multiple rainfall records, whereas the objective here is to demonstrate how the corresponding modelling components can be accessed and combined through Virtual Rain.

Potential failure modes should also be considered when applying the software. Short or incomplete records, very small seasonal wet-day samples, poorly constrained extreme-value fits, weakly identifiable cascade parameters, unsuitable seasonal partitions, or IDF information that is inconsistent with the daily rainfall climatology may lead to unstable or physically implausible parameter estimates. Diagnostic outputs should therefore be considered an integral component of model configuration rather than merely a graphical complement to the final simulation. Where calibration fails to converge or produces parameters outside the theoretically or numerically admissible range, the corresponding configuration should not be used without further investigation.

Overall, the results presented here support the correct operation and internal consistency of the implemented Virtual Rain workflow for the case study considered, rather than establishing universal robustness or transferability of the software across hydroclimates and datasets. The modular architecture nevertheless provides a flexible basis for broader applications, since the two modules can be operated jointly or independently and several model-configuration choices remain accessible to the user. Future evaluations should extend the software assessment to multiple hydroclimatic settings and include systematic uncertainty quantification, parameter-identifiability analyses, sensitivity experiments, matched-length stochastic ensembles, and benchmarking against alternative rainfall-generation and disaggregation tools. Such analyses would complement the methodological evidence already available and provide a more comprehensive assessment of the operational domain of Virtual Rain.

Comment 10

Figure 3. The workflow identifies C_{β} and C_{LN} as calibrated parameters but omits D . Please add D and show where it enters calibration and disaggregation.

Authors' comment: We thank the Reviewer for identifying this omission. We agree that the outer-scale parameter D should be explicitly represented in Figure 3 together with C_{β} and C_{LN} , since all three parameters are involved in the MRC calibration procedure.

Authors' action: Figure 3 has been updated accordingly. The parameter D has been added to the workflow together with C_{β} and C_{LN} , and its role in the calibration stage is now explicitly shown. The revised figure also clarifies that D enters the IDF-based calibration as the outer-scale parameter, whereas the subsequent stochastic disaggregation of the daily rainfall amounts is governed by the calibrated C_{β} and C_{LN} parameters. This modification is consistent with the clarification provided in Section 2.2 regarding the role of D .

Comment 11

Code and data availability placement. Move this section to immediately after the Conclusions and before appendices/acknowledgements, and include the exact version, licence, software citation, and reproduction instructions.

Authors' comment: We thank the Reviewer for this suggestion. We agree that the *Code and data availability* section should provide all the information required to identify, access, cite, and reproduce the archived software release. Regarding its placement, however, we have followed the journal's manuscript preparation guidelines, according to which the relevant sections are presented in the order Conclusions, Appendix, and Code and data availability. We have therefore retained the Code and data availability section immediately after the Appendix, in accordance with the journal's prescribed structure.

Authors' action: The Code and data availability section has been retained after the Appendix, in accordance with the GMD manuscript preparation guidelines, rather than moved immediately after the Conclusions. However, following the substantive part of the Reviewer's suggestion, the section has been substantially expanded to provide the exact Virtual Rain software version, Zenodo DOI, software and data licences, software citation, and detailed reproduction instructions. These additions ensure that the archived release can be unambiguously identified, accessed, cited, and used to reproduce the analyses presented in the manuscript.

The revised section reads:

The Virtual Rain source code, executable routines, documentation, and data used to reproduce the analyses presented in this manuscript are permanently archived on Zenodo (Cappelli et al., 2026; <https://doi.org/10.5281/zenodo.22747568>). The archived release corresponds to Virtual Rain v2 and includes the Python implementation of Module 1, the R implementation of Module 2, the case-study data, and a dedicated README.txt file providing software requirements, input and output descriptions, execution instructions, reproducibility guidance, licensing information, and citation instructions. The Virtual Rain source code is distributed under the GNU General Public License v3.0 or later (GPL-3.0-or-later). The rainfall data used in the case study originate from the Settore Idrologico e Geologico Regionale (SIR) – Regione Toscana and are distributed under the Creative Commons Attribution-ShareAlike 4.0 International (CC BY-SA 4.0) licence. To reproduce the analyses, users should download the archived release and follow the module-specific and complete-workflow instructions provided in README.txt. The archived software should be cited as: Cappelli, F., Grimaldi, S., Petroselli, A., and Santinami, E. (2026): Virtual Rain: A Unified Toolkit for High-Resolution Rainfall Simulation and Disaggregation, Version v2, Zenodo, <https://doi.org/10.5281/zenodo.22747568>.

Comment 12

Capitalization. Use 'Gaussian' rather than 'gaussian' in 'parent Gaussian ACS' and throughout the manuscript. See, e.g., line 89.

Authors' comment: We thank the Reviewer for noting this inconsistency. We agree that “Gaussian” should be consistently capitalized throughout the manuscript.

Authors' action: We have carefully revised the manuscript and replaced “gaussian” with “Gaussian” wherever appropriate, including the expression “parent Gaussian ACS” indicated by the Reviewer.

Comment 13

Typographical error. Change 'inizialize' to 'initialize' or 'initialise', following one consistent English convention. See line 284.

Authors' comment: We thank the Reviewer for identifying this typographical error. We agree that the spelling should be corrected and kept consistent with the English convention adopted throughout the manuscript.

Authors' action: “inizialize” has been corrected to “initialize” at line 284, consistently with the American English spelling convention used throughout the manuscript.

Comment 14

Zenodo metadata. Correct the name 'Samtinami, Emanuele' to 'Santinami, Emanuele', verify ORCIDs, and classify the deposit as software rather than only 'software documentation'.

Authors' comment: We thank the Reviewer for identifying these issues in the Zenodo metadata. We agree that accurate author information, ORCID identifiers, and resource classification are important for the correct identification, attribution, and citation of the archived Virtual Rain release.

Authors' action: The Zenodo metadata have been revised accordingly. The author name “Samtinami, Emanuele” has been corrected to “Santinami, Emanuele”, the author information and associated ORCID identifiers have been checked, and the resource type has been updated to identify the archived release as software, rather than only as software documentation.